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Performance of clay stabilized by cementitious materials and inclusion of zeolite/alkaline metals-based additive

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Abstract

RoadCem (RC) is a ~~by-product~~ additive produced based on nanotechnology and comprises of synthetic zeolites and alkali earth metals as some of its components. The geotechnical properties of a soil stabilized by adding RC to partly replaced cementitious materials are studied. Various combinations of the additives were investigated with the objective of reducing the amount of OPC by 50% by an inclusion of RC and ground granulated blast furnace slag (GGBS) in the stabilized soil. Laboratory studies involving index property testing, oedometer swell-deformation, unconfined compression tests and microstructural examinations were carried out on both the natural and 7-& 28- day cured samples of the stabilized soil. The influence of RC on the mechanical properties of the stabilized soil was examined by comparing the performance of the stabilized soil mixtures that contain the RC and the mixtures without the RC added. Results indicated the positive effect of RC as noticed by the tremendous strength gain in 7 days with the OPC reduced by 50% in the stabilized soil. Swelling decreased significantly to 0% after 28 days curing with the settlement also reasonably reduced for nearly all the percentages of the OPC substituted. The stabilized soil's microstructure revealed the mechanism of cementation observed as an encapsulation or "wrapping effect" as a result of the presence of RC. A comparison of the RC-modified soil containing the by-products GGBS and PFA indicated that GGBS was more effective in the enhancement of engineering properties than PFA. Overall, as well as meeting some of the standards set for road pavement applications,

the results obtained from this research are very promising for the ongoing discussions on reducing carbon foot-printing by OPC replacement.

Keywords: cement; ground granulated blast furnace slag; fly ash; RoadCem; swell; compressive strength.

1. Introduction

Soil stabilization is one of the most economical and effective techniques of ground improvement introduced several years ago with the sole purpose of transforming weak soils to meet certain specific requirements of engineering projects. It involves the alteration of both the physical and chemical characteristics of a soil mass in order to conform to desired properties such as increase in strength, swell reduction, decreased consolidation and increase in durability [1]. Chemical stabilization involving the use of binders or chemicals has been widely applied in the area of transportation engineering with the stabilized soil materials used as improved subgrades, capping layers and sub-bases for roadway or airfield pavements. This method of soil improvement can also aid dust control especially in unpaved roads and highway construction, effective control of water erosion, fixation and leaching control of recycled materials and wastes [2]. Most soil stabilization works in recent times are still relying on the use of the more common or traditional binders such as OPC and lime even though it has been established by research that these binders are economically expensive and environmentally unfriendly [3–6].

On the other hand, the use of industrial by-products, wastes, emulsions, organics and polymers such as ground granulated blast furnace slag (GGBS), pulverised fuel ash (PFA or fly ash), rice husk ash, lime dust, cement kiln dust (CKD), silica, lignosulfonates, etc for the stabilization of weak clay soils, is very promising and have been investigated [7,8,17–23,9–16]. Apart from aiding the enhancement of the engineering properties of weak soils, the introduction of wastes or by-product materials in soil stabilization also guarantees a reduction in the cost of construction as well as preservation of the environment [6].

Some of the industrial by-products and wastes have been used in conjunction with OPC either in a binary or ternary combination to improve the engineering properties of the soil. Table 1 presents a summary from the literature of some of the chemical wastes or by-products materials used with OPC in a compacted soil-binder mass for potential application in pavement subbase and subgrade layers. In most cases, however, the challenges in the usage of these wastes or by-products as partial replacement for OPC still require that more quantities of the OPC be used in the mix proportion given its relatively higher hydration properties.

Hence, the inclusion of minimal quantities of another ~~by-product~~ called "RoadCem" which is produced based on nanotechnology from synthetic zeolites and alkali earth metals does become an alternative in the partially substituted OPC-by-product binder mix. RoadCem (RC) is an additive that is manufactured by the PowerCem Technologies in the Netherlands. Much like most by-products and wastes used in soil stabilization, the RC additive also possesses' good environmental credentials [24]. Only limited studies have utilized the RC additive in the stabilization process but most of the times as an OPC improver in road pavement applications [25–29]. Moreover, it is suggested by its manufacturers that only about 1-2% of the RC be used with the OPC binder in soil improvement in kg/m^3 of the area where it is to be applied [30,31]. Invariably, the challenge of using more quantities of OPC still remains not to mention the attendant concerns previously mentioned.

This study therefore proposes the addition of RC in a soil-binder mixture that includes industrial by-products and the partially substituted OPC in the stabilization process. Hence, an investigation into the geotechnical properties of the stabilized soil by the replacement of up to 50% of OPC by the use of by-products and the RC additives in both binary and ternary combinations will be carried out in this research. The aim is to ensure that the problem of utilizing higher quantities of the OPC in a soil-binder mixture system is further mitigated while also enhancing the engineering properties of the parent soil. A comparison of the effect of using GGBS and PFA in the RC-modified soil shall also be examined.

Table 1. Summary of some chemical wastes and by-products materials used with OPC in soil stabilization.

By-product/waste	Soil type (USCS)	Reference
Alumina-silica	CL	[32]
GGBS	CH	[33–36]
PFA	CL, CH	[2,37,38]
Glass dust	CL	[39]
Metakaolin	CH, MH	[40,41]
Rice husk	CL	[42]
Nano silica	CL	[43]
Volcanic ash	CL	[44]
Silica fume	CH	[45]
Sewage sludge	CL	[46]
Palm oil fuel ash (POFA)	CH	[47]
Zeolite	CL, CH, MH	[48,49]

2. Materials and Methods

The soil material used in this research is kaolinite (China clay) which is commercially processed in powdered form by Mistral Industrial Chemicals in Northern Ireland, United Kingdom (UK). The studied RC additive was supplied by PowerCem Technologies in The Netherlands. The method used to produce this material is based on nanotechnology and is patented by the same company. It is regarded as one of the products in the PowerCem family that contains as some of its constituents, synthetic zeolites and alkali earth metals (Fig 1). The OPC binder utilized was supplied by Hanson Heidelberg group in UK. This OPC complies with the requirements of BS EN 197-1:2011 CEM I Portland cement in the strength class category of 52.5N hence, making it a high strength cement that ensures rapid setting and rapid hardening especially in cold weather conditions. The GGBS used was produced and tested by Hanson Heidelberg cement group UK according to the methods stated in BS EN 196-2:2013. The PFA used in this study was manufactured by CEMEX Cement Limited, UK to comply with the standard regulations of the BS EN 450-1:2012 (loss on ignition Category B and Fineness Category S). The chemical test results carried out by the X-ray fluorescence (XRF) to obtain the main oxide compositions of the soil and binders used are presented in Table 2.

Table 2. Chemical composition of soil and binders

Material	Oxide composition (%)										
	SiO_2	Al_2O_3	Fe_2O_3	CaO	MgO	K_2O	TiO_2	Na_2O	SO_3	Mn_2O_3	LOI
Kaolinite	49	36	0.75	0.06	0.3	1.85	0.02	0.1	-	-	12
OPC	20.7	4.6	2.3	64.0	1.7	0.4	0.3	0.1	2.9	0.1	2.9
GGBS	34.1	13.0	0.51	39.0	9.5	0.5	1.3	0.3	0.3	0.7	1.9
PFA	52.1	30.1	4.0	3.0	1.0	2.1	1.0	2.1	1.2	-	4.0
RC[1]	21.2	1.7	0.63	47.1	4.0	7.46	-	-	-	-	

1. The oxide component not included in the table is H_2O which is 17.9 for RC

Fig 1. Laboratory image of RoadCem additive

2.1 Laboratory procedure and testing

2.1.1 Soil and binder combination programme

The soil was sampled in its natural state and thoroughly mixed in dry form with the binders. 8% of the OPC binder obtained by dry weight of the soil was used. This chosen OPC proportion complies with established procedures for the enhancement of the engineering qualities of the type of soil considered [9,50–54]. Industry recommendation states that about 1-2% (by dry weight of OPC) of RC be used in combination with OPC due to economic and technical reasons [30,31,55]. Since the objective of this study is to reduce OPC by 50%, GGBS being an environmentally-friendly cementitious by-product was used to replace some of the OPC proportions while maintaining the recommended quantity of RC at 1% in the soil-binder mixtures. Other binder combinations with the OPC substituted by 60 and 70% (by dry weight of OPC) were also examined for the sake of comparison. Moreover, in order to further verify and evaluate the effectiveness of GGBS used in the stabilized soil, a comparison was also drawn between the engineering performance of the RC-modified soil mixtures containing GGBS and that which contains another by-product - PFA. The mix design presented in terms of the mixture ratio of their percentages by weight of OPC as well as their respective notations is presented in Table 3.

Table 3. Binder mix design

Mix proportion	1st mix	2nd mix	3rd mix
	% by dry wt. of OPC		
OPC	100	-	-
Notation	OPC100	-	-
OPC: GGBS	50:50	40:60	30:70
Notation	OPC50-GGBS50	OPC40-GGBS60	OPC30-GGBS70
OPC: GGBS: RC	50:49:1	40:59:1	30:69:1
Notation	OPC50-GGBS49-RC1	OPC40-GGBS59-RC1	OPC30-GGBS69-RC1
OPC:PFA:RC	50:49:1	-	-
Notation	OPC50-PFA49-RC1	-	-

2.2 Experimental programme

2.2.1 Index property testing

Determination of the basic engineering properties of the natural and stabilized soil samples was carried out based on required standards. Except otherwise stated, soil testing was performed according to the ASTM standards as given in Table 4 for the natural soil. The Malvern Mastersizer 2000 which uses laser diffraction technology was utilized to analyse the grain sizes of the soil and binders in their dry states and given in Fig. 2. The moisture contents of the samples used in the subsequent performance of the engineering tests were determined at optimum conditions in accordance to ASTM D 1557 as would be required in most pavement works. The moisture contents of the stabilized samples were calculated based on the optimum moisture of the soil sample in its natural state with at least 2% more water added based on experience. Following the compaction test, the samples were removed from the moulds using suitable extractors, wrapped in a cling film and further sealed in zip-lock type bags and preserved for a period of 7 and 28 days to cure at room temperature before carrying out further engineering testing.

Table 4. Properties of natural soil.

Soil property	value	Test standard
Liquid limit	58	ASTM D 4318-1
Plastic limit	30	
Plasticity index	28	
Silt content (%)	74	ASTM D 422-63
Clay content (%)	26	
Specific gravity	2.6	ASTM D 854-10
Modified activity index	0.67	
MDD (kN/m^3)	15	ASTM D 1557
OMC (%)	17	
USCS Classification	CL	
Unconfined compressive strength (kPa)	190	ASTM D 2166
Max swell percent (%)	12.6	ASTM D 4546
Compression index (Cc)	0.109	ASTM D 4547

2.2.2 Unconfined compression test

The unconfined compression strength (UCS) test was carried out by following the procedure stated in ASTM D 2166. The samples were prepared and moulded following the method for the standard proctor compaction according to ASTM D 1557 at the optimum conditions (OMC and MDD). After compaction, standard cylindrical steel of dimensions 76 mm height and 38mmin diameter in dimensions were cored through the compacted samples in the mould, carefully extracted using an extractor jack and then preserved to cure before testing. An average value of UCS was determined and established from at least two similar samples. The rate of axial deformation which was maintained throughout the unconfined compression testing was 1mm/min.

2.2.3 Swell-deformation test

One-dimensional oedometer testing was utilized to determine the free swell-strain of the samples according to the method outlined in ASTM D-4546 at the completion of sample curing. Grease-coated standard oedometer rings measuring 70 mm in diameter and 20 mm in height were inserted into the soil and soil-binder materials in the standard proctor compaction mould and compaction carried out with the rings in the mould. This was done in other to eliminate the problem of breakage or cracking upon the usual coring after compaction and extraction of the samples from the mould. The extracted material was carefully trimmed to remove the soil or soil-binder-laden oedometer ring and preserved to cure. At the completion of curing, the samples were placed in the oedometer apparatus and made to sit in between two porous stones lined with filter papers. The automated load variable displacement transducer (LVDT) was set to zero after recording the initial compression under the seating load of 5kPa. Water was then gradually introduced into the oedometer and the samples soaked or inundated and then allowed to undergo free vertical swelling for a minimum time period of 24 hrs until equilibrium was reached. The swell percent was then calculated as the increase in sample height (Δh) divided by the original height (H) expressed as a percentage.

2.2.4 Consolidation test

Continuous compression done by sequential loading up to a pressure of 1000kPa was ensured on the oedometer samples after the attainment of maximum equilibrium swell with each load sustained for at least 24hrs. The rate of compression determined as the compression index (Cc) was determined from the e-log p plot.

2.2.5 Micro-structural examination

Image analysis to determine the microscopic features of both the natural and stabilized soils were performed in order to explain the change mechanisms that occurred in the samples. This was done by Using the ZEISS EVO equipment to collect the micrographs (SEM) of the cured, dry and completely vacuumed samples. A minimum working distance (WD) of 7.7mm using a minimum acceleration voltage (EHT) of 5.00kV and various degrees of magnifications to obtain clear pictures were observed.

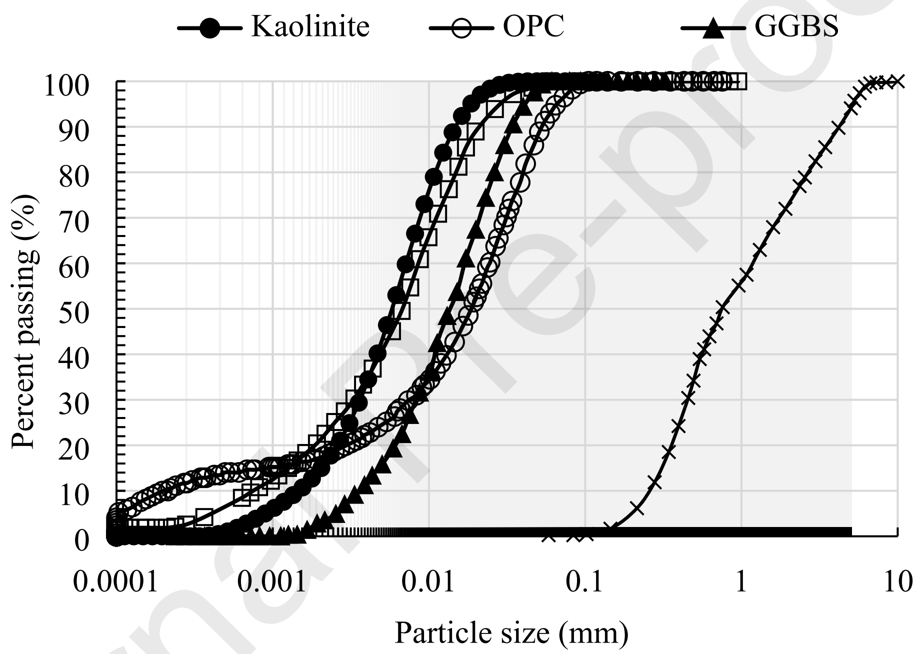


Fig. 2. Analysis of particle size of soil and binders

3. Test results

It will be noticed in the subsequent sections of this research that some of the relevant geotechnical properties of the natural soil stated in Table 4 were in effect much improved when stabilized with all the binders and their combinations. However, in keeping with the goal of this research, the soil stabilized by OPC alone shall be used mostly as a frame of reference when comparing the performance of the respective binder combinations.

3.1 Swell

Figs. 3a & b compare the rate of linear expansion of the binding agents used in the stabilization of the kaolinite after 7 and 28 days of curing respectively. There is a significant drop in the rate of expansion as the curing period increases. Generally, though, for the shorter curing duration, Fig. 3a indicates a progressive increase in the expansion rate as the proportion of OPC in the soil reduces. However, a much closer investigation of the swell-strain path followed by the stabilised soil shows that within about 10-15mins after inundation with water, the lowest expansion does occur in the mixtures with 50 to 60% of the OPC replaced by the by-product additives at 7 days curing period. Nevertheless, at the same curing duration of 7 days, there seems to be only a slight difference in the final expansion (at equilibrium) between the mixture stabilised by OPC alone and that in which 50% of OPC is replaced by the by-product materials. With the curing period extended to 28 days, it can be seen in Fig. 3b that the soil stabilised by using only the cement alone seems to show the highest expansion as compared to the mixtures having the by-products. The rate of expansion is reduced to almost zero with half of the OPC proportion substituted by the by-product additives.

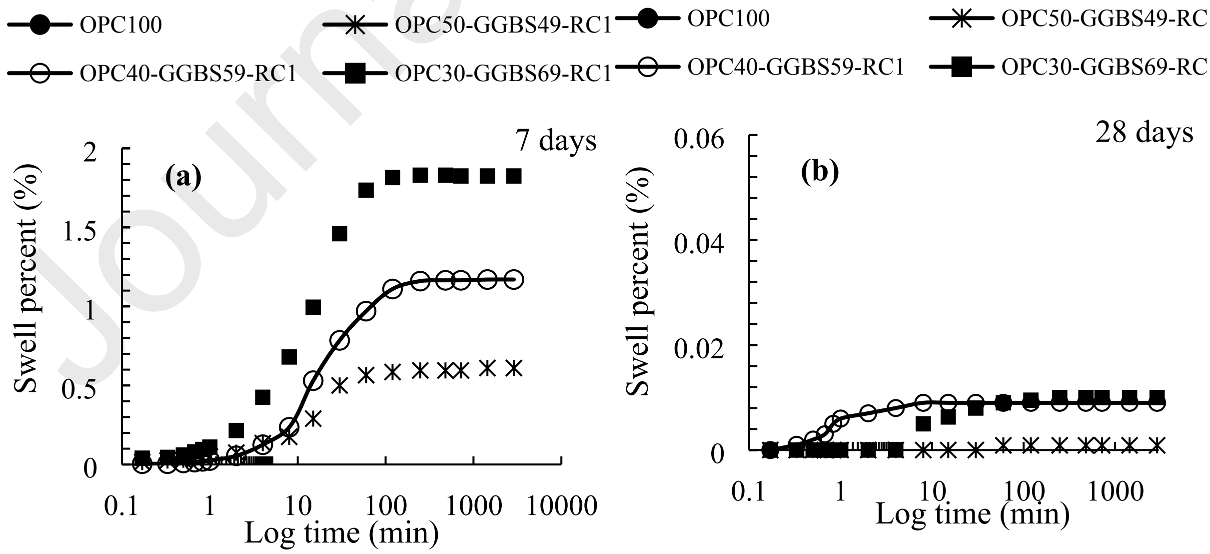
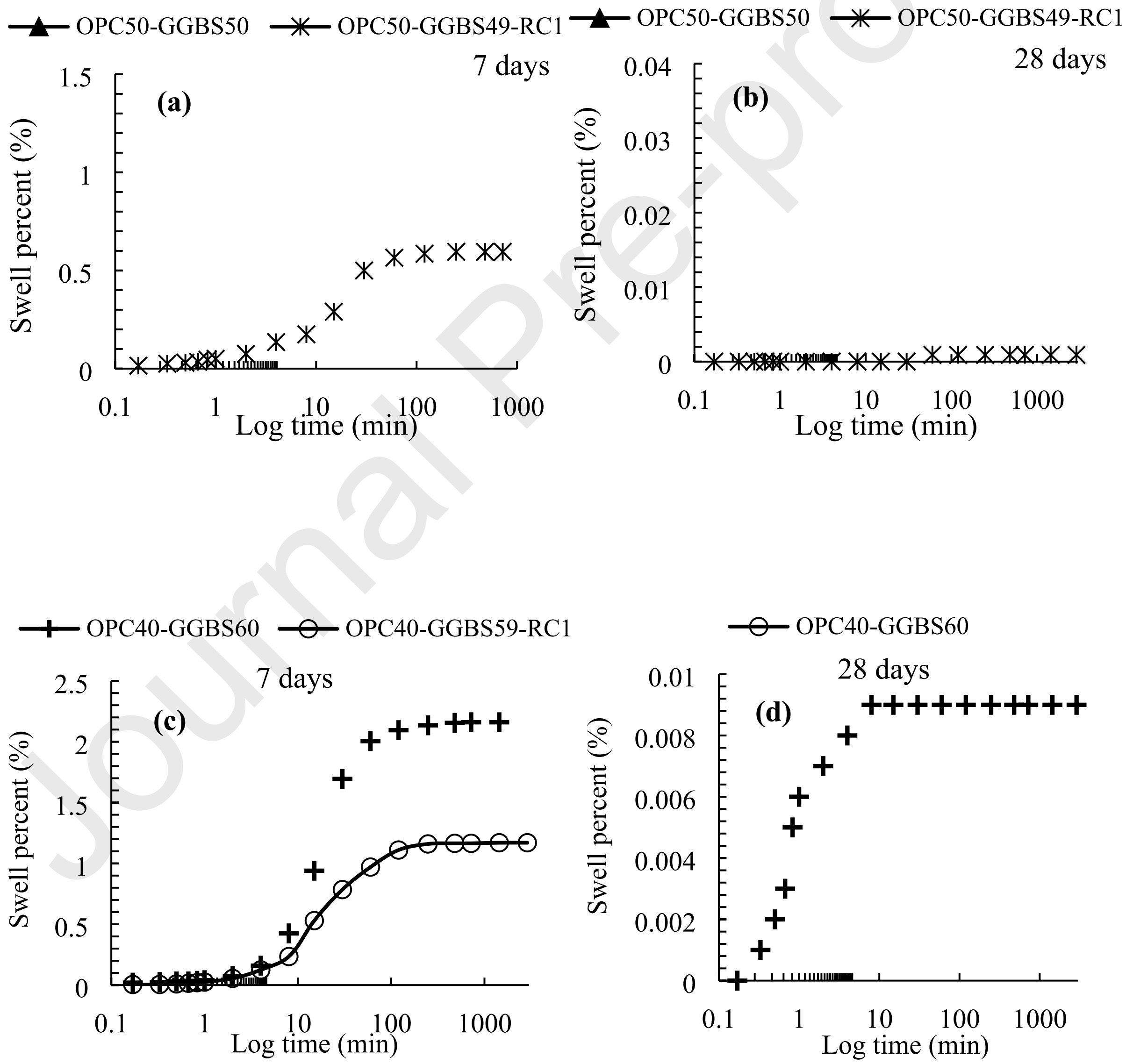


Fig. 3. Swell potential of stabilized soil (a) 7-day cured stabilized soil for 50, 60 & 70% OPC replacement (b) 28-day cured stabilized soil for 50,60,70% OPC replacement.

An examination of the effect of the incorporation of RC in the stabilised soil with up to 50% of the OPC substituted can be readily observed in Figs. 4a-f. Addition of RC to the soil-binder mix reduces the expansion rate to almost zero as compared to the mixture without the RC as the curing was extended to 28 days. At 50% OPC replacement, the percentage difference between the samples that contained RC and those without the RC are 46% and 97% at 7- and 28-days period of curing respectively.



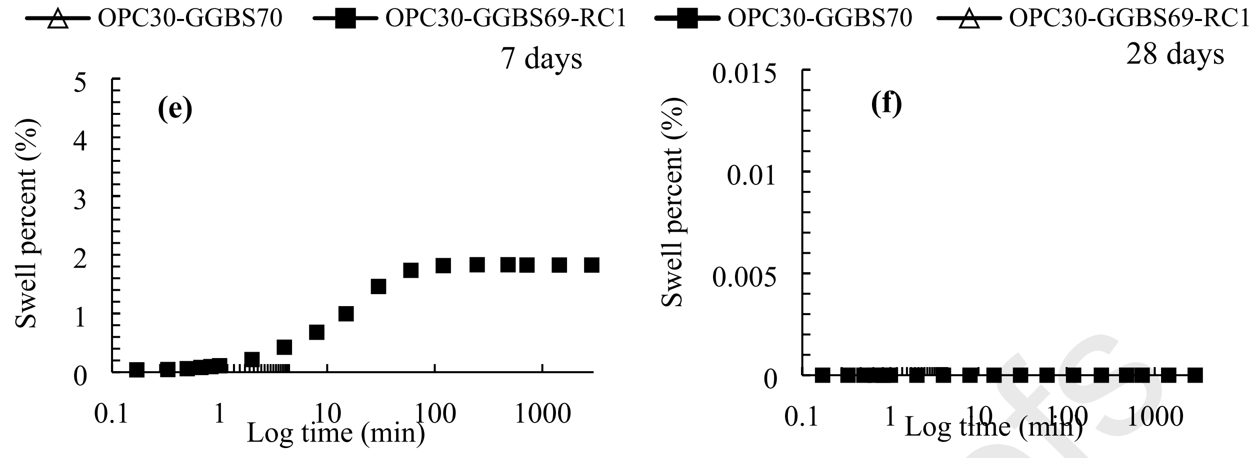


Fig. 4. Stabilized soil swelling showing effect of RC (a) 7-day cured stabilized soil for 50% OPC replacement (b) 28-day cured stabilized soil for 50% OPC replacement (c) 7-day cured stabilized soil for 60% OPC replacement (d) 28-day cured stabilized soil for 60% OPC replacement (e) 7-day cured stabilized soil for 70% OPC replacement (f) 28-day cured stabilized soil for 70% OPC replacement.

Figs. 5a & b show subsequent comparison between the stabilised soil containing GGBS and that having PFA by-products in the RC-modified soil mixtures. It could be observed that the soil-binder mixture having the GGBS seems to reduce expansion more than that in which the PFA is used.

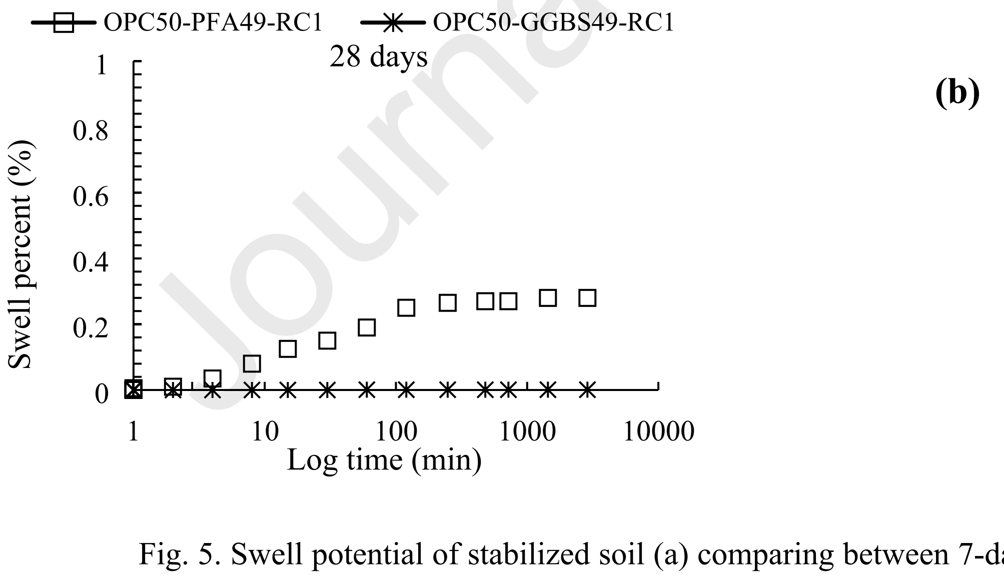


Fig. 5. Swell potential of stabilized soil (a) comparing between 7-day cured RC-modified soil composed of PFA and GGBS (b) comparing between 28-day cured RC-modified soil composed of PFA and GGBS

3.2 Compressibility

The consolidation of the soil-binder mixes is shown plotted on the e-log p curve of Fig. 6. Unlike the case of swell as indicated in the previous section, there appears not to be a huge difference in consolidation rates with the curing time. Nevertheless, as could be observed in Fig. 6a, there is an increase in the initial void ratios of the stabilized soils as the percentage of the OPC binder reduces in the mixtures at 7 days curing duration. Moreover, at the same period of curing, Fig. 6a indicates further that the initial void ratio and the compression path followed by the soil stabilized with only the OPC and the OPC replaced by 50% of the by-products are almost the same. But, as the period of curing increases to 28 days, the soil stabilised by only the OPC seems to have the least initial void ratio Fig. 6b. An examination of the amount of compression is shown in Fig. 7 with much of the compression occurring in the soil-binder mixture with reduced OPC replacement (i.e. 60 and 70% of OPC replaced) with the by-product materials at 7 and 28 days of curing. Although the OPC-only stabilised soil has the least initial void ratio at 28 days of curing, it tends to consolidate more than all the mixtures possessing the by-product additives with 50% of the OPC replaced having the least consolidation (Fig. 7).

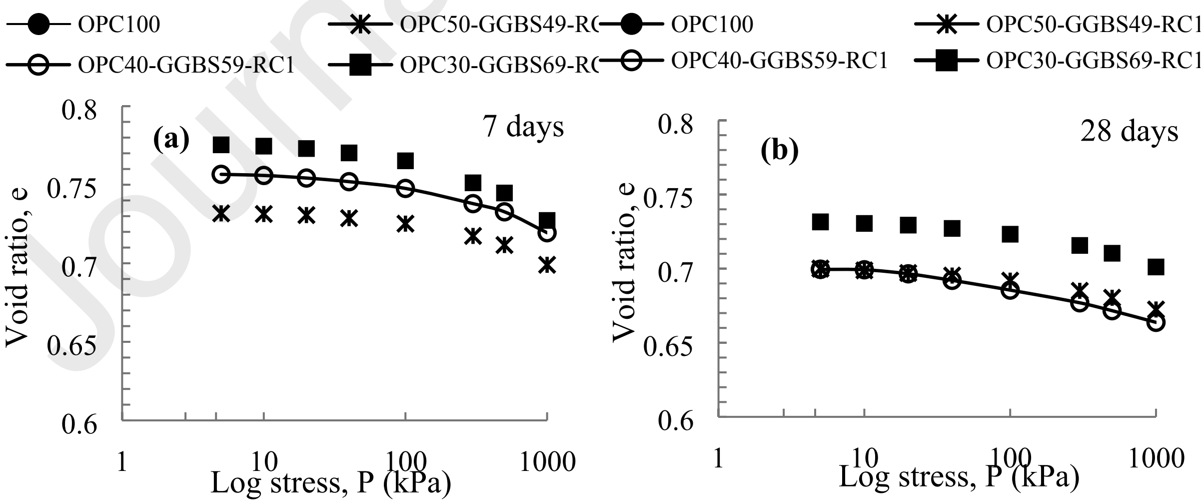


Fig.6. Stabilized soil consolidation and compression index (a) e vs. log P curve of 7-day cured stabilized soil for 50, 60 & 70% OPC replacement (b) e vs. log P curve of 28-day cured stabilized soil for 50, 60 & 70% OPC replacement.

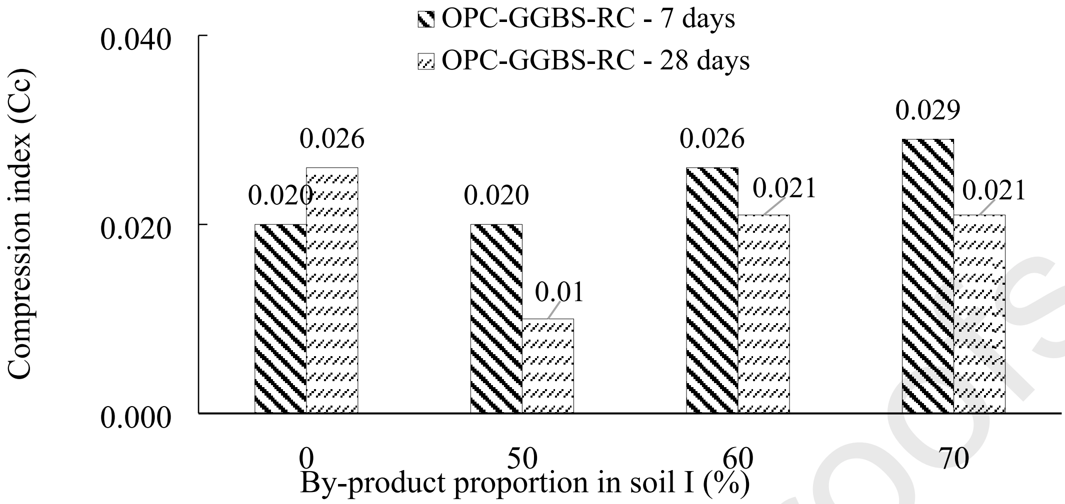
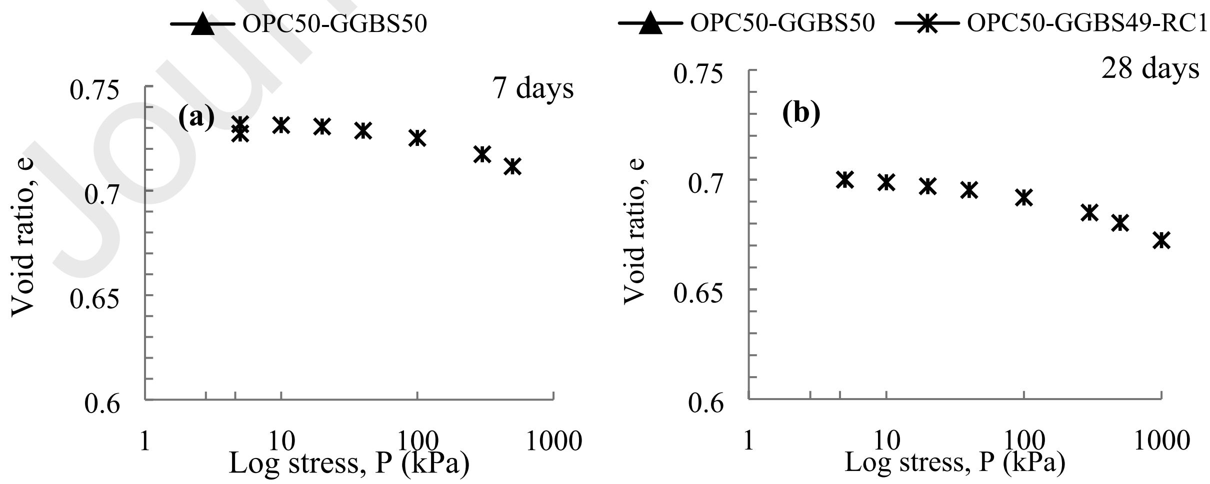


Fig.7. Stabilized soil compression indices of 7- & 28-day cured stabilized soil for 50, 60 & 70% OPC replacement.

Figs. 8a-f show the e log p curve that indicates the influence of RC in the stabilized soil. However, in terms of the settlement rate, comparing the soil stabilised mixture with 50% of OPC replaced with the by-product having RC and without RC reveals that the mixture having the RC seems to consolidate much less than that without the RC at 7- and 28-days curing with the difference being approximately 30% and 50% respectively (Figs. 9a & b).



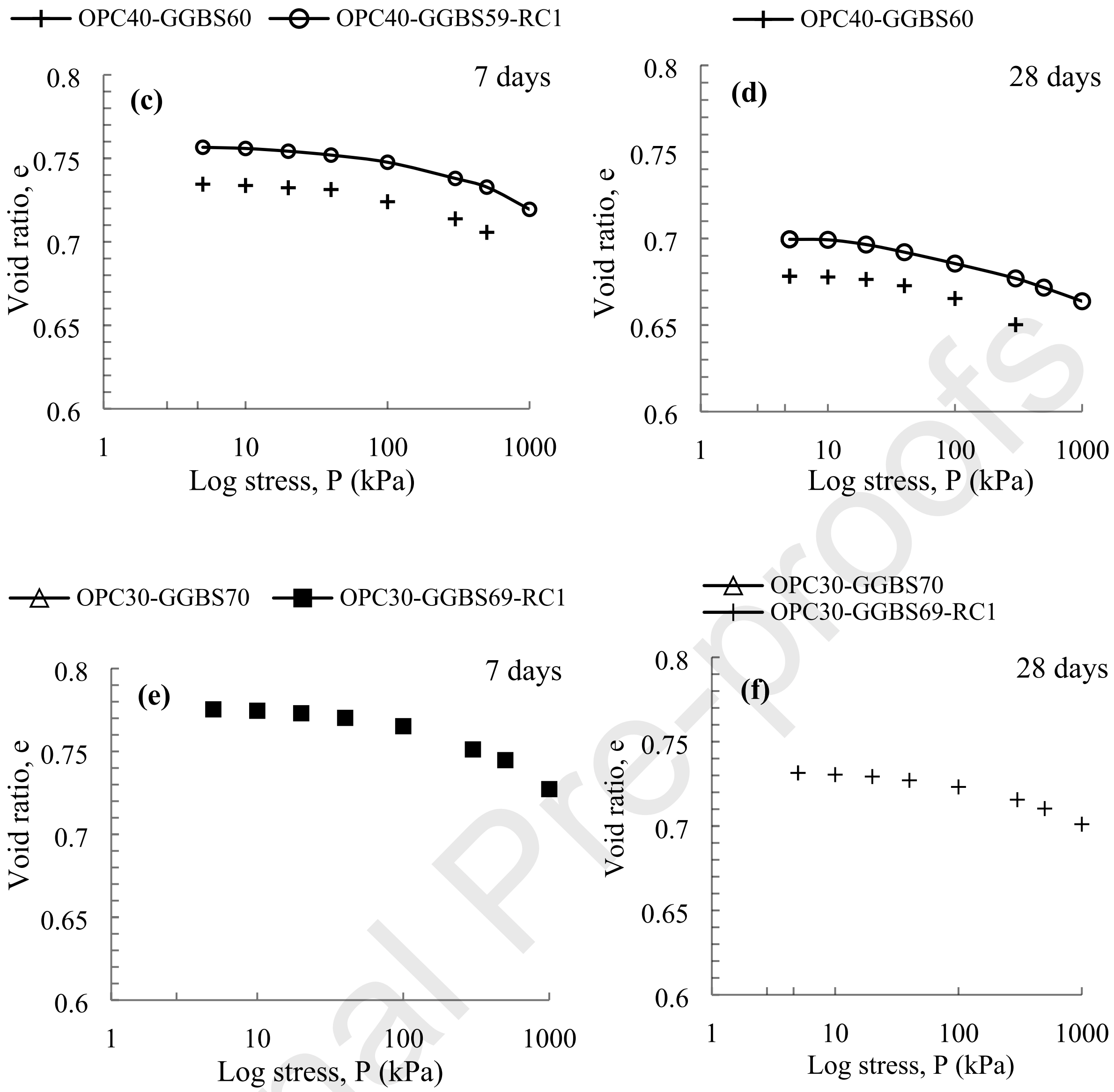


Fig. 8. Stabilized soil e vs. log P consolidation curve showing effect of RC (a) 7-day cured stabilized soil for 50% OPC replacement (b) 28-day cured stabilized soil for 50% OPC replacement (c) 7-day cured stabilized soil for 60% OPC replacement (d) 28-day cured stabilized soil for 60% OPC replacement (e) 7-day cured stabilized soil 70% OPC replacement (f) 28-day cured stabilized soil for 70% OPC replacement.

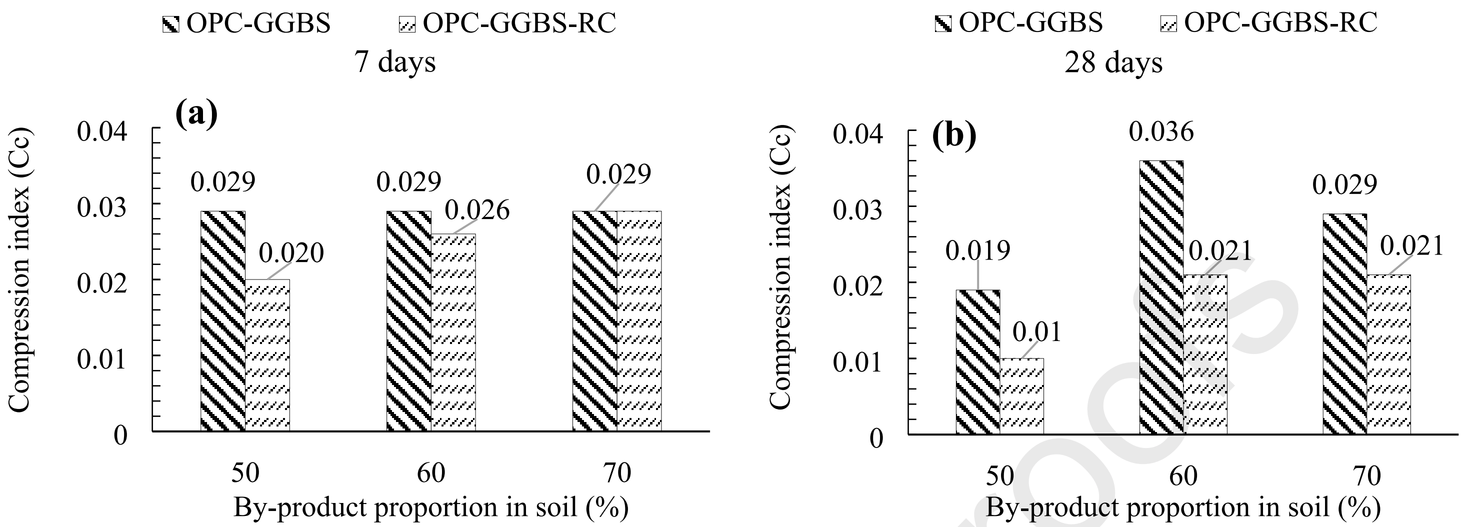


Fig. 9. Stabilized soil compression index showing effect of RC (a) 7-day cured stabilized soil for 50, 60 & 70% OPC replacement (b) 28-day cured stabilized soil for 50, 60 & 70% OPC replacement.

A further comparison between the by-products GGBS and PFA contained in the 50% OPC substituted mixtures with the RC added are given in Fig. 10 and Fig. 11. As could be observed there seems to be a rather large difference in the initial void ratios and in the compression index (Cc) between the soil-binder mixtures containing GGBS and that having the PFA. It is clearly obvious here that OPC-by-products containing the GGBS is more effective in reducing settlement than that which consist of the PFA.

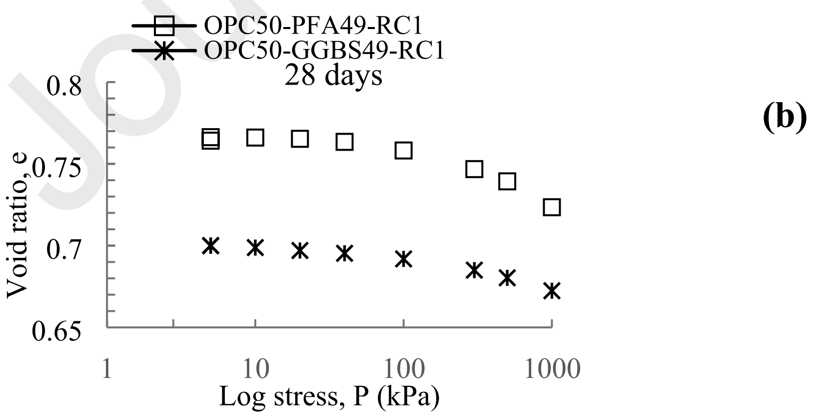


Fig. 10. Comparing the consolidation curves of stabilized soil containing PFA and GGBS (a) 7-day cured stabilized soil (b) 28-day cured stabilized soil.

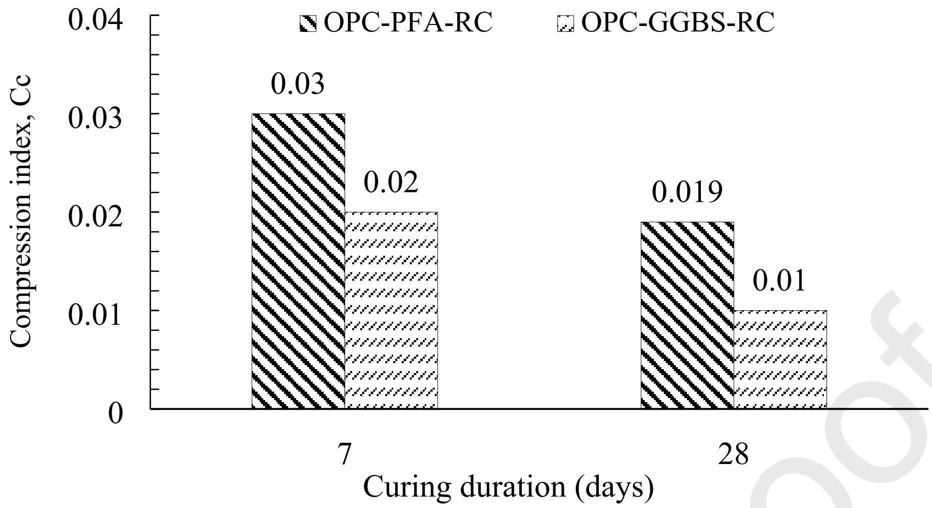


Fig. 11. Comparing between compression indices of 7-& 28-day cured stabilized soil composed of PFA and GGBS.

3.3. Unconfined compressive strength (UCS)

The UCS of all the OPC-by-product combinations in the stabilized soil increases generally more than the OPC-only stabilized soil at 7 days of curing (Fig. 12a.). The percentage gain in strength (peak value) between the soil stabilized by OPC used alone and that in which half of the OPC proportion is replaced is about 80% at 7 days of curing. However, after 28 days of curing the samples, the strength gained in the soil-binder mixtures containing OPC alone seems to rise more remarkably to slightly more than twice of its maximum strength value at 7 days. There is also a noticeable but relatively slow increase in strength occurring in the OPC-replaced mixtures at over the 28 days period of curing. Nevertheless, the strength of the stabilized soil with the OPC replaced by 50 and 60% of the by-products are both higher than the that of the soil stabilized using only OPC (Fig. 12b).

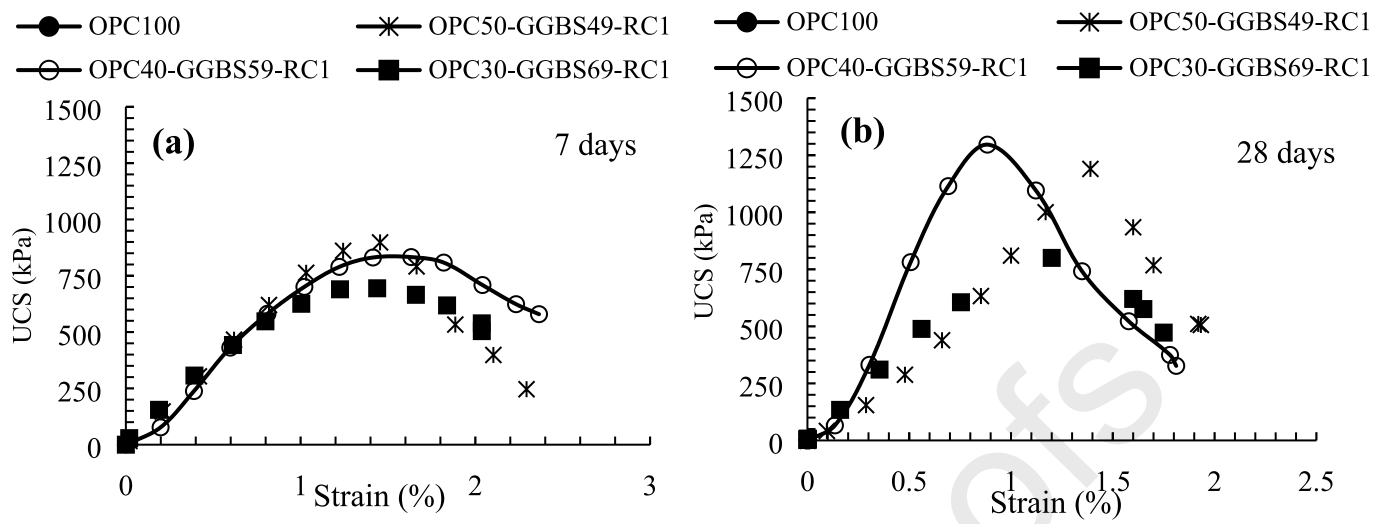
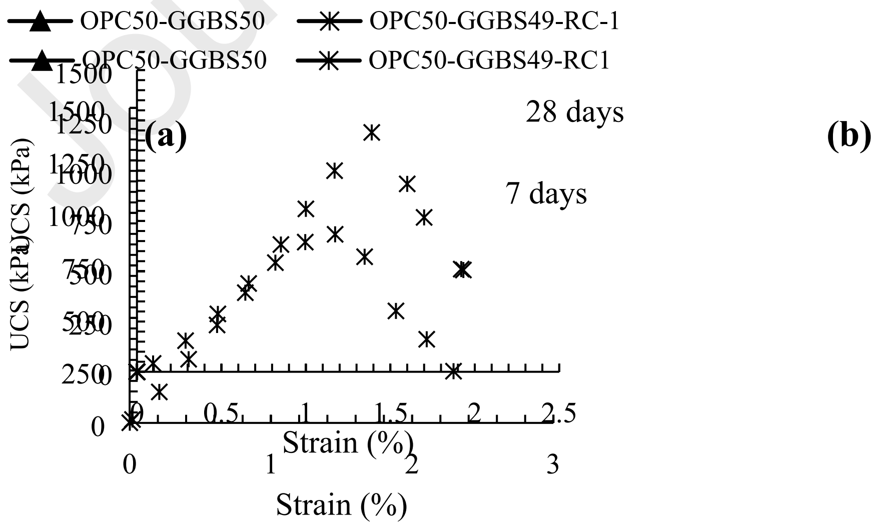


Fig. 12. Unconfined compressive strength of stabilized soil (a) 7-day cured stabilized soil for 50, 60 & 70% OPC replacement (b) 28-day cured stabilized soil for 50,60,70% OPC replacement

When comparing the mixtures without RC and that in which RC is added, it could be seen in Figs. 13a-f that at 7 days of curing, the peak value of the UCS of the mixture without RC is only slightly less than that containing the RC. But, with the curing extended to 28 days, the mixture without the RC tends to increase more than that having the RC. This interesting occurrence could be related to the e-log p curve (Fig. 8) where the mixture without the RC had a slightly less initial void ratio at the start of consolidation as compared to the mixture that contains the RC. Hence, the rate of strength gain for the samples containing the RC seems to be slightly slower than the samples without the RC.



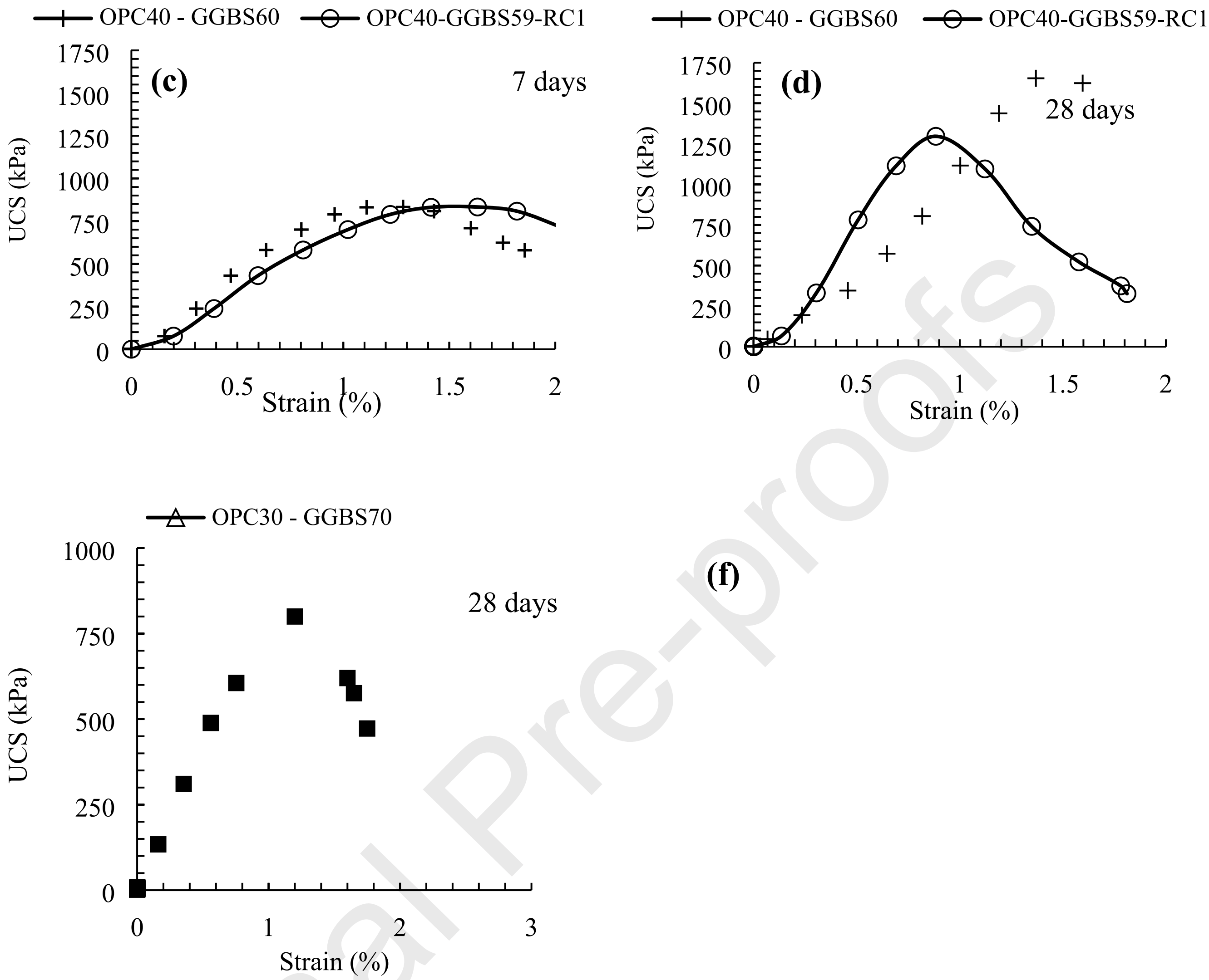


Fig. 13. Unconfined compressive strength of stabilized soil indicating the effect of RC (a) 7-day cured stabilized soil for 50% OPC replacement (b) 28-day cured stabilized soil for 50% OPC replacement (c) 7-day cured stabilized soil for 60% OPC replacement (d) 28-day cured stabilized soil with and without RC for 60% OPC replacement (e) 7-day cured stabilized soil for 70% OPC replacement (f) 28-day cured stabilized soil for 70% OPC replacement

In terms of the type of by-products used in stabilizing the soil, it could be seen in Figs. 14a & b that the soil-binder combinations that includes GGBS seem to have much more improved strength as compared to that in which PFA is used with 50% of the OPC replaced at 7 and 28 days of curing.

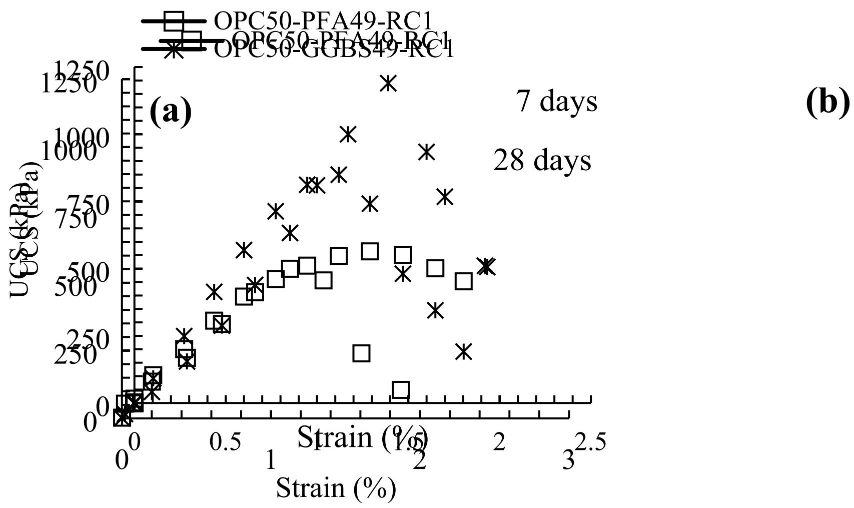


Fig. 14. Stabilized soil unconfined compressive strength (a) comparing between 7-day cured RC-modified soil composed of PFA and GGBS (b) comparing between 28-day cured RC-modified soil composed of PFA and GGBS.

4. Discussion

4.1 Treatment mechanism and microstructure of stabilized soil

An observation of the compacted natural soil (Fig. 16a) reveals a somewhat leafy or flaky structure. This suggests an interlinked pore structure with the capacity to absorb water at a high rate due to increased permeability. When natural kaolinite is exposed to excessive moisture, an aspect of swelling regarded as inter-crystalline swelling occurs [56–58]. The adsorption of water (which possesses just a thin monolayer thickness) onto the negatively-charged surfaces of the mineral thus creates a concentration gradient between a double-diffused layer (consisting of the water molecules and exchangeable cations) and the existing bulk solution. On the other hand, stabilization of the soil by OPC or GGBS utilized in this research enables a modification of the created electrical double-diffused layer by causing a reduction of its thickness, hence leading to a reduction in expansion when inundated by water. Depending on the amount and type of OPC or GBBS used, the decrement in swelling could be attributed to the reduced affinity of the soil to the adsorb water within a shorter period of curing of say 7 days due to the process of continuous agglomeration and flocculation (Fig. 16b). However, with the progress of time, the formation of crystalline cementitious or fibrous pozzolanic products of hydration (CASH, CSH or CAH) develops (Fig. 16c) which aids a further reduction in swell, decrease in settlement and an increase in the strength of the stabilized soil. The complex reaction products that are formed from the mechanism of cementitious materials such as OPC and GGBS have been thought of as capable of developing into a spherical barrier (Fig. 15) that can preclude further production of hydration products by not allowing penetration and reaction of the binders with soil [59]. However, with the addition or introduction of RC into the soil-binder mixture, the barrier already created by the cementitious products is broken which then enables a deeper entrance of it and more water of hydration into the soil particles leading to an increase in the pH value of the soil. More of the crystalline hydration products is certainly formed at this stage with the growth of the crystals into the voids that were left in the initial hydration [30]. It is this enhanced crystallisation which is sometimes accompanied by a decrease in the heat of hydration that does eventually lead to the improvement of the mechanical properties of the stabilized soil when RC is added. Fig. 16d indicates the formation of an interlocking matrix (or what is referred to as the "encapsulation or wrapping effect" [30,31]) created as a result of RC addition to the soil in the presence of cementitious binders.

It was observed by Ventura and Koloane [28] that the addition of 1% RC to a soil-OPC-PFA mixture would improve its mechanical characteristics. However, as could be observed in this research, the use of GGBS seems to enhance the strength more than the stabilized soil mixture with the PFA included (Fig. 14). The rate and type of the formed pozzolanic products of hydration in a soil-OPC-by-product system are determined mainly by the by-products (GGBS or PFA) themselves [60]. The activation of the by-products by OPC and the constituents in the soil promotes the hydration of the by-products with the subsequent formation of the hydration products mostly as time progresses. The introduction of a supplementary additive like the RC does further enhances the process by acting as a catalyst to quicken OPC hydration either simultaneously or subsequently, the hydration of the by-products. Since the mechanical properties of the stabilized soil system are much improved when the GGBS is added than with the PFA, it is believed that GGBS which is more hydraulic in nature and containing much of the Ca^{2+} may have been activated much quicker and thus was involved in the production of more of the cementing products.

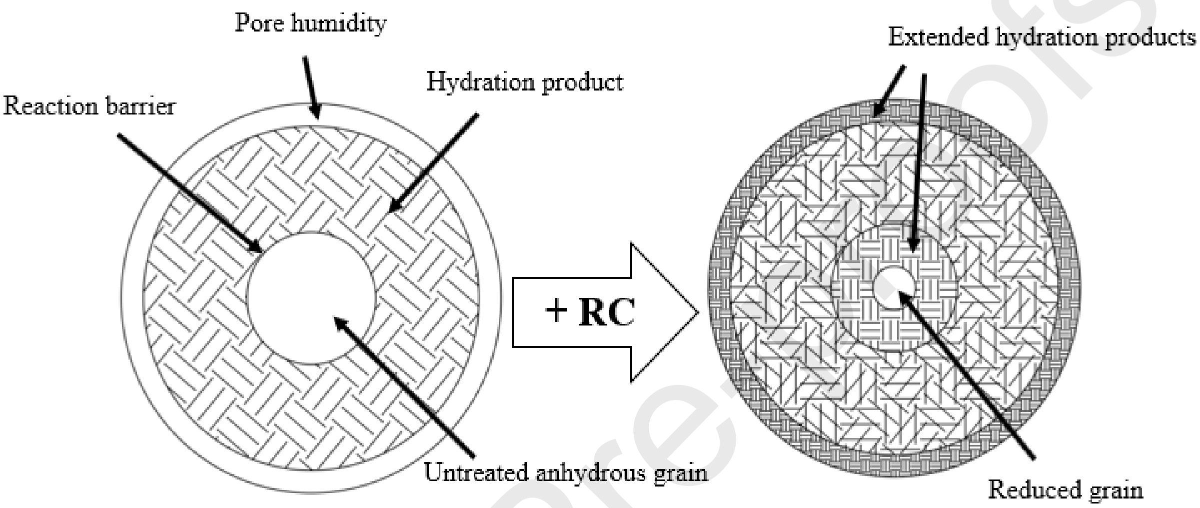
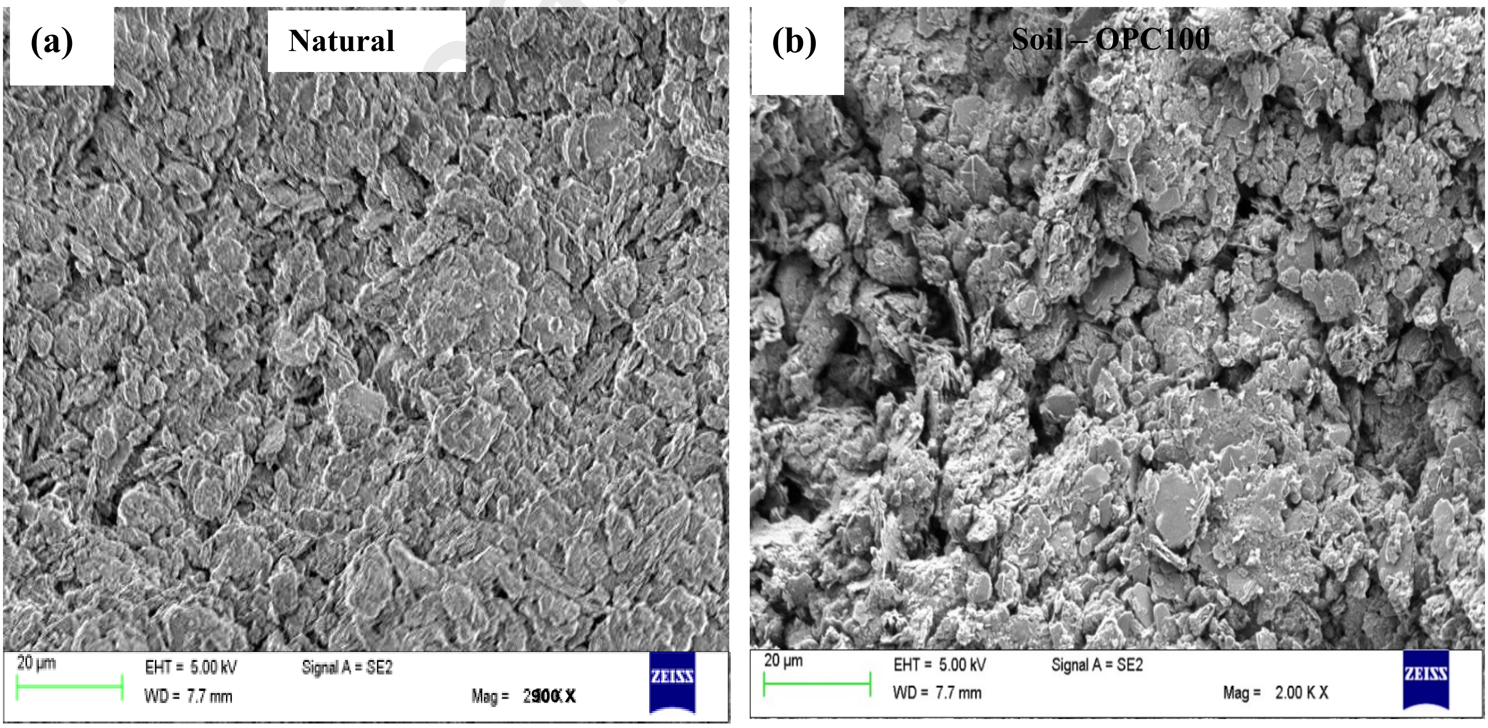


Fig. 15. Description of mechanism of stabilization with the inclusion of RC



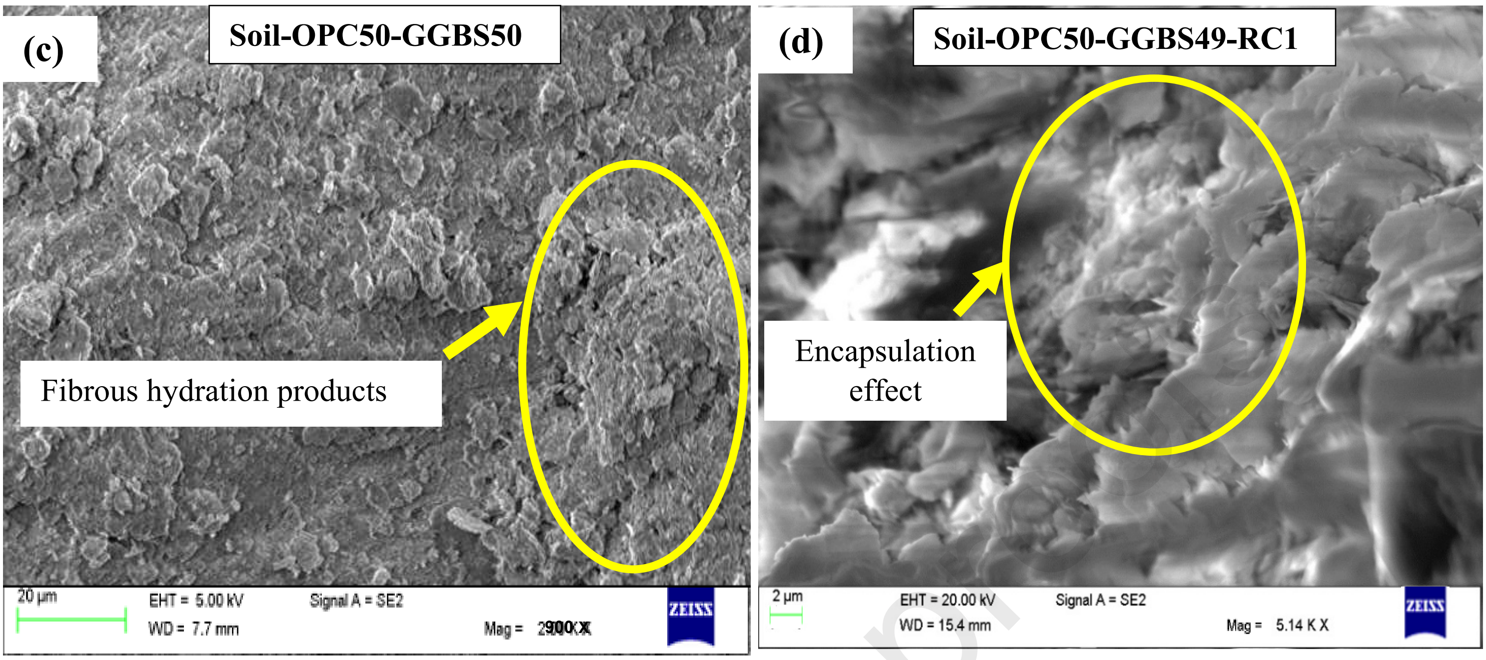


Fig. 16. Micrographs of stabilized soils (a) Natural soil (b) SEM of OPC-stabilized soil (d) SEM of OPC-GGBS – stabilized soil (e) SEM of stabilized soil by inclusion of RC.

4.2 Applicability of the stabilized soil

4.2.1 UCS

The UCS serves as an important index in construction and aids the determination of the usability and effectiveness of compacted natural and stabilized soil samples. The (ASTM D 4609) for instance recommends a benchmark of about 0.35 MPa for an effective stabilization with binders. Hence, the UCS for all the soil-binder combinations considered above could be said to be effective generally following the ASTM standard. However, when considering more specific applications, for example pavement construction, different establishments, ministries and agencies require some minimum values to meet the target UCS for subgrade and subbase layers. This invariably means that the standard or minimum value of the UCS has not been set universally but depends on the needs and requirements of a particular region or country given the sets of conditions existing there. Except otherwise stated, the quoted values that are mentioned herein are those determined by the agencies the testing protocols of which follows closely those adopted in this research. For instance, a range of UCS values between 0.7-1.4 MPa has been suggested for road sub-base and subgrade construction by the American Concrete Institute, Ingles and Metcalf and the U.S Corps of Engineers, [61–63], for OPC-stabilized soils at 7 days of curing. Also, an interim report by the Transportation Centre in the University of Kentucky in conjunction with the Transportation Cabinet Commonwealth and the Federal Highway Administration U.S. Department of Transportation [64] did suggest a 7-day UCS of 0.71MPa for an OPC-stabilized subgrade. Elsewhere, the Standard Specification for Road Works for Flexible Pavements in Malaysia [65] recommends a 7-day UCS of 0.8MPa for the subgrade construction. It could be observed here that the OPC-stabilized soil for the 7-day UCS value in Fig. 12a does not seem to meet these conditions. Meanwhile, the OPC-by-product combinations do satisfy the above requirements at 50-60% of the OPC replaced by the by-products (that includes GGBS and RC) under 7 days of curing (Fig. 12a). Notice also that the OPC-by-product material combination with the PFA and RC included do not fulfil the above-mentioned required standards for UCS at 50% OPC replacement proportion (Figs. 14**)**. On the other hand, the newly edited guide by the road transport and traffic agencies in Australia and New Zealand [66] recommends a maximum 28-day UCS of cementitiously-modified pavement materials to be 1MPa. The soil stabilized by inclusion of the sustainable OPC-GGBS-RC binder combinations (with the OPC replaced by 50% by-products) surely meet this requirement (Figs. 12b).

4.2.2 Consolidation

Even though soil consolidation is rarely used as a standard criterion for the selection of binders for soil treatment in pavement works, a sufficiently reduced rate of consolidation would be desirable to prevent undue settlement and failure of the road structure. Ouhadi et al., [51] in their study, attempted the use of compression index, Cc of stabilized soft clay, suggested as a practical standard for the determination of the optimum binder proportion for the stabilization. 8% (by dry weight of soil) of the cement calculated by dry weight of the weak soil used in the stabilization resulted in a reduction in Cc of about 90% at 7 days of curing even though the optimum cement content was fixed at 6% (the proportion by which further addition of cement only resulted in very minimal change in Cc, that is, the curve had become asymptotic to the relevant axis). In this research, it was observed in Fig. 7 that the 50% OPC substitution by the by-products containing the RC additive caused a reduction in Cc of approximately 80% in 7 days but with an even greater reduction of about 90% occurring at 28 days of curing.

4.2.3 Swell potential

Soil swelling or expansion is a crucial phenomenon in pavement construction and should not be ignored. Research and certain agency standards have suggested the minimum expansion that should be acceptable for treated soils to be considered for the construction of roads. About 0.6% swell percent (95% reduction at 7 days) occurred when the OPC-GGBS-RC combination (at 50% OPC replaced) were used (Fig. 4a). Curing of up to 28 days led to 0% and to nearly 0% for all the proportions 50% replacement of the OPC with the by-products (Fig. 4b). Even though not utilising the same method of testing as proposed by this research, The NF P 94–100 [67] have recommended a minimum of 5% swell as acceptable for construction. Ingles and Metcalf [61] suggested a 2% minimum swell strain for OPC treated soils at 7 days of curing while the Ohio Department of transport [68] recommends 1.5% swell percent for chemically treated soils.

5. Conclusion

Soil stabilization using cementitious materials and inclusion of an additive called RoadCem (RC) produced based on nanotechnology is studied. The following conclusions are made:

1. 50 to 70% of the by-product used to replace OPC led to an obvious decrease in the swelling property of the soil with the best trend observed with the addition of RC to the stabilized soil as compared to the OPC used alone in the stabilization process. Moreover, results also confirmed the effectiveness of using GGBS as an OPC replacement as compared to PFA.
2. A notable increase in the compressive strength of stabilized soil indicated the effect of RC with the highest strength value obtained at a shorter curing period (7 days) when 50% of the OPC was replaced hence meeting most of the minimum requirements for pavement subgrade application.
3. Consolidation and settlement properties decreased significantly as time progressed with the soil stabilized by substituting the OPC used with nearly all the proportions of the by-products containing RC.
4. Scanning electron micrographs utilized to study the stabilized soils' features revealed the binding mechanism noticed as an interlocking microstructure thus, confirming the mechanical improvement occurring due to the addition of RC as compared to using OPC alone in the soil stabilization.

6. Reference

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